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A NATIONAL SYSTEM FOR THRESHOLD RUNOFF ESTIMATION

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ABSTRACT

Threshold runoff is the amount of effective (or excess) rainfall of a given duration uniformly distributed over a certain catchment that is just enough to cause flooding at the outlet of the draining stream. Threshold runoff estimates, when used in conjunction with operational soil moisture accounting models and radar rainfall data, are an essential component of a flash flood warning system. Threshold runoff estimates can be determined by equating the peak catchment runoff, as computed from the catchment unit hydrograph of the given duration, to the stream flow at the catchment outlet at the time of flooding. Geographic Information Systems (GIS) and distributed terrain elevation data bases have been used to support the application of the aforementioned hydrologic/hydraulic principle to natural flash-flood prone catchments on a regional scale. The software package *threshR* has been developed to determine threshold runoff estimates without manual intervention. Snyder's unit hydrograph and a geomorphologic unit hydrograph have been used as options to determine the catchment peak runoff rate. Manning's steady, uniform flow resistance formula and the two-year return period flow have been used as options to determine the flood flow at the outlet of the draining stream. To a large extent use of any permutation of the aforementioned options depends on available data. Results of error analysis are presented that show the accuracy of catchment delineation by the GIS software, and the accuracy of the *threshR* threshold runoff estimates as compared to those computed manually using existing unit hydrographs of selected catchments.

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INTRODUCTION

As part of its Modernization Program, the National Weather Service (NWS) has undertaken to design and implement improved, as well as consistent, procedures for the determination of Flash Flood Guidance (FFG) values. Such values are used for issuing Flood Warnings for small streams throughout the United States. This paper is focused on the first step in improving the current flash flood procedures, i.e., the computation of physically based local threshold runoff values (applicable to small streams) used to produce the flash flood guidance values (*Sweeney, October 1992*). This approach builds upon existing procedures and can be implemented quickly compared to potentially more accurate procedures involving distributed, physically-based catchment models that are envisioned for the future.

Specifically, the first step is to develop and implement a procedure for the determination of threshold runoff values of a given duration over a region for the purpose of estimating the corresponding FFG-values in real time. In this context, a threshold runoff value (also referred to as an R-value) is the rainfall excess volume that accumulates over a catchment during a certain time period t_R and which is just enough to cause flooding of the draining stream at the outlet of the catchment. Rainfall excess refers to the rainfall residual obtained after subtracting catchment losses due to infiltration and evaporation from rainfall. The rainfall excess volume is assumed distributed uniformly over the time period t_R and over the catchment area. Flooding can operationally be identified by either the bankfull flow or the flow of a certain return period. Flash flood guidance values are obtained from threshold runoff values through the use of a soil moisture accounting procedure that estimates the amount of rainfall lost to evaporation and infiltration. Operational implementation consists of obtaining a set of curves that relate threshold runoff values (R-values) to FFG-values for different antecedent moisture conditions using the operational soil moisture accounting procedures at a typical River Forecast Center (RFC) of which there are 13 throughout the U.S. The soil moisture accounting procedure that corresponds to each area of interest (in terms of its parameter values) is used. Then, using the curve that corresponds to the most recent soil moisture condition as updated by the RFC from the R-value of a given duration t_R, the FFG-value of duration t_R is obtained for each location. Comparison of this value with the radar-observed rainfall of the same duration and at the same location forms the basis for the determination of whether a flash flood warning will be issued for that site. Of interest is areal flash flood guidance, with the FFG-values computed on a uniform grid superimposed over the region. The size of such a grid is related to the size of the grid used for the radar rainfall products (approximately 4 km by 4 km).

Several assumptions are embedded in the threshold-runoff problem definition that may dictate better applicability to certain areas than to others:

(a) The assumption of uniform rainfall excess over the catchment embeds limitations with respect to catchment size and infiltrability properties. The temporal rainfall uniformity limits applicability to short time scales (e.g., less than a few hours).

(b) Flooding flows are usually associated with damage to property and are very difficult to determine nationally. The bankfull discharge used as a surrogate for a flooding discharge has the problem that, in many channels, the channel cross-section varies considerably in space in short distances and in time (due to the occurrence of floods). Also, bankfull discharge is rarely associated with actual flooding conditions and it is a rather conservative measure of flooding when used for flash flood guidance. On the other hand the flow with a certain return period is not a physical quantity but a statistical concept, which, however, entails the notion of risk associated with flooding. There is evidence of a good statistical relationship between bankfull discharge and the

discharge with a return period between 1 and 2 years (e.g., see discussion in *Henderson, 1966, pgs. 464-467*).
(c) Interpolation to uniform grid implies spatial smoothing of the field of values with the local character lost in the interpolation.

THRESHOLD RUNOFF

It is pre-supposed that the method for R-value determination should be based on sound hydrologic and hydraulic principles for spatial coherence and reliability and that it should be computationally efficient given the scale of required computations. It is important that estimates for the free parameters of the procedure be computable and stable over a region given the available national databases. Since it is imperative that a method for R-value determination is developed that is suitable for use on a national scale, it is required that the method can utilize digital terrain elevation databases with national coverage and Geographic Information System (GIS) software.

The method of determination of a threshold runoff value for a certain catchment stems from the R-value definition when it is assumed that the catchment responds linearly to rainfall excess (i.e., unit hydrograph theory applies). Thus, if R denotes the threshold runoff value of a certain duration t_R, Q_p denotes the flooding discharge at the outlet of the catchment, A denotes the catchment area, and q_{pR} denotes the peak discharge of the t_R-duration unit hydrograph of the catchment in units of discharge per unit volume of rainfall excess per unit area, the definition of the R-values implies:

$$Q_p = q_{pR} R A \qquad (1)$$

Solving for R yields:

$$R = \frac{Q_p}{q_{pR} A} \qquad (2)$$

The problem then becomes one of determining Q_p, q_{pR} and A from observed field data that are expected to be available on a national basis. As a general guideline, utilization of GIS software and national digital terrain elevation databases allows the determination of geometrical catchment characteristics. Channel cross-sectional characteristics that determine Q_p cannot be resolved with present-day GIS database resolution. If the option requiring channel characteristics is implemented, then site visitation would be required for representative samples of stream geometry in a region. In the following, we present several options that allow the determination of R from Equation (2) given different data-availability scenarios and given the general approach adopted by the U.S. National Weather Service at the present time.

The value of Q_p can be determined through the use of a flow resistance formula (e.g., Manning's formula for turbulent flow conditions, *Chow, et al. 1988, pg. 33-39*) to relate the runoff discharge to the channel geometrical and roughness characteristics for bankfull flow conditions. It can also be approximated by the stream discharge with a two-year return period (discharge that is expected to be equalled or exceeded once every two years). The two choices correspond to two different philosophies for determining the flooding discharge Q_p and require a different set of parameters which need different sets of field data. In both cases, however, the data is limited and not available on a uniform basis over the U. S. Regionalization of the required parameters is necessary for each case in order to estimate their values in ungauged catchments from the values observed in a few catchments in the region of analysis. Stability of the regionalized relationships and data availability are expected to be the main factors in making a choice between the aforementioned two ways of computing Q_p.

Synthetic unit hydrograph theory can be utilized to determine the relationship between the effective rainfall of a given duration and peak runoff discharge and timing given geometric drainage basin characteristics as parameters (e.g., Snyder's synthetic unit hydrograph, *Chow, et al. 1988, pg. 224-228*). It is also possible to utilize the recently formulated geomorphologic instantaneous unit hydrograph theory (*Gupta, et al. 1986*, also in *Bras, 1990*) to avoid the use of empirical coefficients that depend on "observed" unit hydrographs, which exist for very few flash-flood prone catchments. In the case of the geomorphological unit hydrograph, regionalization is also necessary. We note here, that both approaches utilize the assumption of linearity for the catchment response which is fundamental within unit hydrograph theory (*Chow, et al. 1988, pg. 214*). We also note that past application and analysis have shown that results based on the linearity assumption are worse for small catchments (see *Wang, et al. 1981* for a review and analysis) and, for a given catchment size, are better when the rainfall intensity increases (e.g., *Caroni, et al. 1986*).

Once regionalized relationships have been established for the parameters of interest, substitution in the procedure for computation of Q_p and q_{pR} gives R-values which can be compared for each of the several procedures outlined above. The choice of the procedure involves considerations of data availability for a certain region, and stability (indicating small variance about the regression line) of regionalization relationships (e.g., for a certain area, the channel bankfull width may have a more stable relationship to catchment area than the hydraulic depth of the draining channel).

The procedure for the determination of R-values is part of the GIS software implementation that: (1) isolates regions for analysis given digital terrain elevation data, (2) determines the catchments within the region, and the drainage network within catchments together with relevant geometrical characteristics, (3) runs the R-value program for each catchment, and (4) displays the results on a stream network of the region, associating an R-value with the outlet of the corresponding catchment and/or with the relevant catchment area. The next section outlines the GIS procedure development and presents results of sensitivity analysis.

GIS PROCEDURE

The first consideration regarding the use of GIS is the available digital databases (*USGS, 1989*). National coverage at the present time is achieved by the 1° by 1° digital maps (also referred to as Defense Mapping Agency maps). Such maps are utilized in the analysis with the 7.5 minute map series used for verification of the procedures. The various steps for GIS analysis are as follow:

> *A GRASS window is defined around each USGS-defined Hydrologic Cataloging Unit (CU). R-values are determined independently for each CU. After defining the GRASS window (GW) and the MAPSET for the CU, the CU boundary vectors are converted to a GRASS cell file. Each USGS DMA file falling within GW is converted into a cell file. The EPA River reach stream file for the CU inside the GW is then converted to a cell file. The various files are then combined to form a mosaic. The mosaic is scanned to check for zero elevation seams at the junctions. A cubic spline surface generation algorithm is used to mend these seams. Watershed analysis is then performed using the software R.WATERSHED. Parameters relevant to the R-value computation, such as basin areas and slopes, are extracted from the detailed output of R.WATERSHED. R-values are computed for each basin. An inverse-distance-squared interpolation procedure is used to convert basin threshold runoff estimates to gridded runoff estimates.*

The software package R.WATERSHED has been developed by *Ehlschlaeger (1990)* and it determines catchments by moving upward from the lowest-elevation sections of the digital map. Land is given to the drainage basin which encroaches it first. When two basins meet, a ridge is formed. The travel uphill is done one contour line at a time. Digital data other than the elevation data can be used to increase the accuracy of the procedure. Several tests of the procedure were made with 7.5 minute and 1 degree digital maps. In all cases R.WATERSHED correctly identified all basins and streams even in very flat areas. Only at the boundaries of the analysis maps the procedure fails. Such a problem does not affect the accuracy of the results because a substantial grace margin around the CUs has been used.

ERROR ANALYSIS AND PROSPECT

Estimates of catchment area and stream length produced by the GIS were compared to corresponding quantities as measured manually from 7.5 minute maps for several streams in Oklahoma and Iowa. The errors in area for areas less than 200 sqkm were less than 15 percent in all cases examined. The errors in stream length for stream lengths less than 30 km were less than 35 percent. The average registration errors in the location of streams, in units of distance, as compared to estimates from the EPA stream files (manually digitized from topographic maps) were less than 0.4 km.

Threshold runoff values (R-values) corresponding to the four possible options (two options for flooding flow and two options for the unit hydrograph peak in Equation 2) for a few streams in Iowa with measured channel cross-sectional data are shown in Table 1 as R1 through R4. Geomorphologic unit hydrograph theory was used for R1 and R2, while Snyder's synthetic unit hydrograph was used for R3 and R4. The 2-year return period flow was used for R1 and R3. bankfull flow was used for R2 and R4. Also shown are the R-values corresponding to two-year return period flow, R-Q2, and bankfull flow, R-Qbf, computed from Equation 2 using unit hydrograph peaks derived from historical data of 15-minute flow and hourly rainfall. No specific calibration was performed for any of the options of R-value computation using GIS. Average values from the literature were used for the two empirical parameters of Snyder's synthetic unit hydrograph. During the manual processing of the historical data, events were identified that caused less than bankfull flows (in some cases substantially less due to historical data availability) and a very simple procedure has been used to separate baseflow for the construction of the historical unit hydrographs. The options using geomorphologic unit hydrograph theory have produced R-values that are remarkably close to the manually obtained ones using the historical data, in view of the uncertainty associated with unit hydrograph estimation from historical records. In order to improve the performance of the options using Snyder's synthetic unit hydrograph it is planned that implementation of it will include parameter calibration using nearby stream gauge information.

Table 1

Hourly Threshold Runoff Values in Inches

	Manual		threshR			
Stream Name	R-Q2	R-Qbf	R1	R2	R3	R4
Timber Creek	0.4	0.4	0.4	0.5	0.6	0.8
Salt Creek	1.0	0.6	0.5	0.4	0.8	0.6
Walnut Creek	0.4	0.6	0.5	0.6	0.7	0.9
Rapid Creek	0.4	0.4	0.8	0.8	1.0	1.4
Richland Creek	0.3	0.4	0.5	0.6	0.8	0.9

Verification with data from several other streams in Iowa and in Oklahoma is in progress, the main issue with the realization of such verification procedure being the availability of channel cross-sectional data. Of course, final verification of the threshold runoff theory and the resultant flash flood guidance values will be done in an operational environment.

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APPENDIX I - REFERENCES

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